Evaluating On-Farm Flooding Impacts on Soybean

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ABSTRACT

Flooding is a major problem that reduces soybean [*Glycine max* (L.) Merr.] growth and grain yield in many areas of the USA and the world. Our objective was to identify the plant and soil characteristics associated with different flooding durations in six fields in central Ohio. The soybean plants were at the V2 and V3 stages when rainfall-induced flooding occurred. The outer perimeters of the flooded areas were mapped, using GPS (global positioning system) technology, several times during the flooding event to delineate the change of the flooded area over time. Two 9-m wide transects across the flooded area within each field were divided into plots of 9 m by 9 m according to flooding duration: no flooding, 1 to 3 d, 4 to 6 d, and 6 to 8 d. Soil and plant nutrient levels, grain yield data and grain protein and oil content were determined for each plot. The soil cation-exchange capacity (CEC), pH, P, Ca, Mn, and Zn concentrations had significant positive correlation with flooding duration. There was a significant negative correlation of flooding duration with the population, height, number of pods, and yield of soybean. There was no significant correlation of flooding duration with seed weight, oil, or protein content of the seeds. Leaf tissue Ca, Mg, B, Fe, Cu, and Al concentrations had a significant positive correlation with flooding duration, whereas leaf tissue N concentration had a significant negative correlation with flooding duration.

Flooding from excessive rainfall or irrigation compromises soybean growth and grain yield (Stanley et al., 1980; Oosterhuis et al., 1990; Russell et al., 1990). Natural flooding can be classified into two categories: (i) stream flooding, characterized by the overflow of rivers or creeks into a flood plain; and (ii) lowland flooding, characterized by inadequate surface drainage and slow soil permeability of depressional areas. Flooding can be further divided into either waterlogging, where only the roots are flooded, or complete submergence where the entire plants are under water. It was estimated that waterlogging for as little as 2 d at the V4 growth stage (Fehr and Caviness, 1977) reduced soybean grain yield by 18%, while the reduction was 26% at the R2 stage (Scott et al., 1989). According to VanToai et al. (1994), waterlogging for 4 wk at R1 to R2 stages reduced the average grain yield of 84 soybean cultivars by 25%. Heatherly and Pringle (1991) reported that 1 to 2 d of waterlogging caused by flood irrigation did not reduce soybean yield, but longer periods of waterlogging resulted in significant yield losses.

Research at the ARS Soil Drainage Research Unit has shown that contrary to the injury of soybean in flooded fields, it can thrive in stagnant water in the greenhouse (Boru et al., 1997). Soybean grown in hydroponic medium continuously bubbled with N gas where the dissolved oxygen level was not detectable showed no symptoms of stress. Soybean, therefore, is much more tolerant to excessive water and lack of oxygen than previously expected (Grable, 1966; Sallam and Scott, 1987; Russell et al., 1990). The reasons underlying the dramatic differences between responses to flooding in the greenhouse and flooding in the field are not known; however, growth reduction and yield loss in flooded fields could have arisen from root rot diseases (Schmitthenner, 1985), N deficiency (Fausey et al., 1985), nutrient imbalance (Barrick and Noble, 1993), and/or the accumulation of toxic levels of CO_2 in the root zone (Boru et al., 1997). Since flooding injury is affected by many factors, including variety, growth stage (Linkemer et al., 1998), flooding duration, soil type, fertility levels, and pathogens, an understanding of the interaction of these variables would provide insight useful to the development of flood-tolerant soybean cultivars.

The objective of this study was to conduct on-farm research to identify plant and soil characteristics associated with different flooding durations in six fields in central Ohio.

MATERIALS AND METHODS

Site Description

The study was conducted in 1998 at six production field sites in central Ohio where flooding frequently occurs (Table 1). The Champaign (CH), Franklin (FR), Pickaway 1 (P1), and Union (UN) sites contain depressional areas that are subject to lowland flooding. The Pickaway 2 (P2) and Fayette (FA) sites are in the floodplain where flooding is due to stream overflow. Roundup Ready (Monsanto, St. Louis) soybean cultivars were planted without tillage at all sites. The cultivar names and other agronomic practices are reported in Tables 1 and 2.

Each field was mapped several times during a flooding event in June, 1998, using a Precision Lightweight Global Receiver model PLGR + 96 (Rockwell, Cedar Rapids, IA) GPS to delineate the change of the flooded area over time.

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Abbreviations: CEC, cation-exchange capacity; CH, Champaign site; FA, Fayette site; FR, Franklin site; GPS, global positioning system; P1, Pickaway 1 site; P2, Pickaway 2 site; UN, Union site.

Table 1. Coordinates, soybean variety, planting date, planting density, row spacing and previous crop of each of the six farm sites in this study.

Site	Coordinates†	Soybean variety	Planting date	Planting density	Row spacing	Previous crop
				plants ha^{-1}	cm	
Champaign	−83.8239571 40.1310406	Beachley Hardy 346 RR	5/16/98	469 490	37.50	Corn
Franklin	−83.0112739 39.8090939	Pioneer 9294 RR	5/15/98	494 200	37.50	Corn
Pickaway-1	−82.9747300 39.6561728	Countrymark 3597 RR	5/06/98	494 200	18.75	Corn
Union	−83.4893209 40.2067154	Shur-Grow 377 RR	5/19/98	494 200	18.75	Corn
Fayette	−83.5266392 39.4603894	AsGrow 4401 RR	5/31/98	555 975	37.50	Soybean
Pickaway-2	−82.9801820 39.5654033	Dekalb CX 420 RR	4/20/98	402 611	50.00	Soybean

† Coordinates are North American Datum 83/GRS80.

Two parallel transects, each 9-m wide, were laid out across the flooded area and extended into the nonflooded area within each field. Transect length varied from site to site, depending on the size of the flooded area, with the shortest at 64 m (CH) and the longest at 124 m (P1). Each transect was divided into 9- by 9-m plots in which soil and plant parameters and final yields were measured. The plots were grouped into four treatments according to flooding duration: no flooding, 1 to 3 d, 4 to 6 d, and 6 to 8 d. For simplicity, these are referred to as 0-, 3-, 6- and, 8-d flooding durations. The number of plots for each flooding duration and the total number of plots for each site are reported in Table 3.

Each site was represented by more than one soil type (Table 4). The orders of the soil series were Mollisols, Alfisols and Inceptisols with the drainage classification ranging from very poorly drained to well drained, and surface texture from silt loam to silty clay loam. These soils have a low to moderate shrink-swell capacity.

Temperature and rainfall for each site (Table 5) were collected by remote sensing and supplied by Grower Service (Detroit, MI). This information is not site based and may not be as accurate as on-site measurements, but does reflect the weather conditions of each site.

Plant Parameters

Plant population, plant height, leaf tissue elemental analysis, number of nodes and pods, seed size, grain yield, and grain oil and protein content were determined for each treatment plot. Plant population was determined at the V4 growth stage, after flooding, by counting the number of plants per 0.9-m row randomly selected at three places in each plot. Plant height was determined by measuring the distance from ground level to the tallest point of three randomly selected R1 plants per plot. Leaf samples for elemental analysis were collected from the uppermost trifoliate of ten randomly selected R1 plants. The leaves were dried at 70°C for 48 h, ground to powder, and P, K, Ca, Mg, Mn, Zn, B, Fe, Cu, Al, and total N were analyzed by flame ionization (AOAC, 1990) at the Service Testing and Research Laboratory, Ohio Agricultural Research and Development Center, Wooster, OH. Yield components were determined on four randomly selected R8 plants per plot by counting the number of nodes and pods per plant and determining seed size (100-seed wt.). Grain oil and protein content were determined by the near infrared transmittance method (Williams and Norris, 1987) at the USDA-ARS, National Center for Agricultural Utilization Research, Peoria, IL. Grain yield was determined by harvesting the transect with commercial combines equipped with a GPS receiver and yield monitor, except at the Union site where a similarly equipped plot combine was used.

Table 2. Rates of fertilizer and herbicide application at each site.

Site	P_2O_5	K_2O	Preplanting herbicide	Postplanting herbicide
	– kg ha^{-1} –		g ai ha^{-1}	
Champaign	0	134	2,4-D (538) sulfentrazone + chlorimuron (79)	Glyphosate (1119)
Franklin	0	0	Glyphosate (560) Cloransulam-methyl (176)	Glyphosate (1119)
Pickaway-1	0	0	Glyphosate (560) 2,4-D (538)	Glyphosate (841)
Union	0	0	2,4-D (538) sulfentrazone + chlorimuron (79)	Glyphosate (1119)
Fayette	56	224	Glyphosate (560) 2,4-D (269)	Glyphosate (1119)
Pickaway-2	0	0	N/A	Glyphosate (1119)

Soil Parameters

Three soil samples were randomly collected in each plot to ≈0.18-m depth with a 2.5-cm-diam. soil probe when the plants were at the R1 stage. The samples from each plot were combined, air dried, ground and analyzed for pH (1:1 water) (McLean, 1982), organic matter content by loss on ignition (Nelson and Sommers, 1982), and CEC (Warncke and Brown, 1998). Soil chemical analyses to determine P, K, Ca, Mg, Mn, Zn and B concentrations were conducted as described by Warncke and Brown (1998) at the Service Testing and Research Laboratory, Ohio Agricultural Research and Development Center, Wooster, OH.

Statistical Analysis

Correlation analysis was performed using the Statgraphics Software Package (Manugistics, Rockville, MD) to quantify the degree of positive or negative linear relationship between flooding duration and each of the associated soil and plant parameters for each of the six sites. The flooding duration was used as the independent variable and was assumed to have

Table 3. Number of plots for each flooding duration and total number of plots at each site.

Flood duration (d)	0	3	6	8	Total plot number
Champaign	3	9	2		14
Franklin	8		6	6	20
Pickaway-1	14	14			28
Union	8	11	3		22
Fayette	6	14			20
Pickaway-2	4	15	7		26
Total	43	63	18	6	130

Table 4. Soil classification and drainage classes of each site.

Farm site	Soil series	Taxonomic classification†	Drainage class‡
Champaign	Homer	Fine-loamy, *Aeric Ochraqualf*	SPD
	Lippincott	Clayey over sandy-skeletal, *Typic Argiaquoll*	VPD
Franklin	Eldean	Fine *Typic Hapludalf*	WD
	Ockley	Fine-loamy *Typic Hapludalf*	WD
Pickaway 1	Wea	Fine-loamy *Typic Argiudoll*	WD
	Ross	Fine-loamy *Cummulic Hapludoll*	WD
	Princeton	Fine-loamy *Typic Hapludalf*	WD
Union	Lippincott	Clayey over sandy-skeletal, *Typic Argiaquoll*	VPD
	Celina	Fine *Aquic Hapludalf*	MWD
Fayette	Miamian	Fine *Typic Hapludalf*	WD
	Patton	Fine *Typic Hapluquoll*	VPD
Pickaway 2	Warsaw	Fine-loamy over sandy-skeletal, *Typic Argiudoll*	WD
	Genesee	Fine-loamy *Typic Udifluvent*	WD
	Eldean	Fine *Typic Hapludalf*	WD

† All soil series were in the mixed mesic family.
‡ MWD, moderately well drained; SPD, somewhat poorly drained; VPD, very poor drained; WD, well drained.

a uniform probability density function with a linear cumulative distribution function of zero on the 0th d, and one on the 8th d (Siddall, 1993; Soboyejo, 2000). On the basis of this assumption, the following values were assigned to each flooding duration for the correlation analysis: 0 for 0 d of flooding, 0.375 (3/8) for 3 d of flooding, 0.75 (6/8) for 6 d of flooding and 1 (8/8) for 8 d of flooding. Within each site, the data from plots with similar flooding duration were treated as multiple samples, and comparisons between flooding duration treatments were based on the Student's *t* test.

RESULTS

The total precipitation for the 1998 growing season at the six sites ranged from 44.9 cm at FR to 55.08 cm at CH (Table 5). The normal precipitation in central Ohio during the five-month growing season is 50.5 cm. The rainfall distribution, however, was highly variable. Rainfall on 14 June caused flooding at the CH, FA, and UN sites when the plants were at the V2 growth stage. Rainfall on 30 June caused flooding at the FR, P1, P2, and UN sites when the plants were at the V3 growth stage. The duration of flooding varied from site to site, so the number of plots and treatments varied as shown in Table 3. Late in the growing season, there was evidence of drought stress on the well-drained soils of the FR, P1, and P2 sites, because of low rainfall in July and August.

The degree of positive or negative linear relationship between flooding duration and each plant and soil property at each site are reported in Table 6. The correlation between flooding duration and each plant and soil property is site specific. In general, a significant and negative correlation existed between flooding duration and population, height, number of pods per plant, yield, leaf tissue N concentration, and soil B concentration. There was also significant positive correlation between flooding duration and the following soil and plant parameters: CEC, soil pH, soil P, Ca, Mn, and Zn concentrations, and leaf tissue Ca, Mg, Fe, Cu, and Al concentrations.

The plant population for each flooding duration and each site is reported in Fig. 1. The FR and P2 sites had low populations on the nonflooded areas probably due to poor germination. The stand at the P1 and UN sites was greater than the seeding rate reported by farmers indicating problems with the reported seeding rates. All the plants at FA died after 3 d of flooding but no reduction in population was found at the CH, P1, P2 and UN sites. Flooding for 6 d ultimately reduced the plant population at the P2 and UN sites, but still did not affect the population at the CH and FR sites.

Table 5. Monthly weather data during the 1998 growing season at each site.

Location Temperature (°C) Precipitation (cm)	May	June	July	August	September	Total precipitation for the growing season
Champaign						
Average temperature	18.94	21.3	22.7	23.2	21.1	
Total precipitation	6.55	20.50	16.51	10.16	2.03	55.75
Franklin						
Average temperature	19.4	21.8	23.3	24.2	21.7	
Total precipitation	6.58	23.34	6.91	2.51	5.54	44.88
Pickaway 1						
Average temperature	18.8	21.3	22.7	23.0	20.8	
Total precipitation	6.27	20.37	5.08	8.71	8.31	48.74
Union						
Average temperature	18.8	21.3	22.7	23.2	21.1	
Total precipitation	7.39	19.10	12.85	4.62	1.24	45.20
Fayette						
Average temperature	19.1	21.4	22.9	23.7	21.5	
Total precipitation	14.63	14.38	11.30	7.42	3.18	50.91
Pickaway 2						
Average temperature	18.8	21.4	22.7	23.0	20.9	
Total precipitation	6.76	22.28	3.89	9.73	4.90	47.56

Table 6. The linear association (R) between flooding duration and soil and plant parameters at each site and their probability values (P).

	CH		FR		P1		UN		FA		P2	
Farm site	R	P	R	P	R	P	R	P	R	P	R	P
CEC	0.52	0.06	0.74	0.01	0.24	0.20	0.48	0.03	0.61	0.01	0.66	0.01
OM	−0.03	0.90	0.01	0.90	0.47	0.02	0.05	0.80	0.39	0.10	0.37	0.06
pH	0.59	0.03	0.76	0.02	0.15	0.50	0.04	0.90	0.41	0.08	0.24	0.20
Soil P	0.80	0.01	0.50	0.07	0.29	0.20	0.16	0.50	0.18	0.40	−0.47	0.01
Soil K	0.59	0.03	0.42	0.01	0.63	0.01	0.52	0.01	−0.22	0.40	−0.39	0.05
Soil Ca	0.48	0.08	0.80	0.20	0.21	0.30	0.44	0.04	0.77	0.01	0.79	0.01
Soil Mg	0.61	0.02	−0.29	0.01	0.29	0.10	0.38	0.07	0.76	0.01	−0.44	0.02
Soil Mn	0.72	0.01	0.57	0.01	0.50	0.01	−0.07	0.70	−0.13	0.60	0.78	0.01
Soil B	−0.49	0.07	−0.71	0.01	−0.12	0.50	−0.26	0.20	0.02	0.90	−0.36	0.07
Soil Zn	0.04	0.90	0.69	0.01	−0.07	0.70	−0.32	0.10	0.51	0.02	0.84	0.01
Leaf N	0.11	0.70	−0.77	0.01	−0.50	0.01	−0.60	0.01			−0.22	0.30
Leaf P	−0.11	0.70	−0.06	0.01	−0.14	0.50	−0.02	0.90			0.78	0.01
Leaf K	−0.58	0.03	0.76	0.01	0.03	0.90	0.42	0.05			0.36	0.07
Leaf Ca	0.27	0.40	0.85	0.01	0.74	0.01	0.66	0.01			0.83	0.01
Leaf Mg	−0.32	0.30	0.84	0.01	0.73	0.01	0.42	0.05			0.62	0.01
Leaf Mn	−0.30	0.30	0.14	0.60	−0.19	0.30	0.03	0.90			−0.42	0.04
Leaf B	−0.55	0.04	−0.32	0.20	−0.25	0.20	0.78	0.01			0.66	0.01
Leaf Zn	−0.23	0.40	0.01	0.90	−0.49	0.01	0.04	0.90			0.89	0.01
Leaf Fe	0.24	0.40	0.77	0.01	0.25	0.20	0.39	0.41			0.52	0.01
Leaf Cu	0.01	0.90	−0.17	0.50	−0.27	0.20	0.60	0.01			0.85	0.01
Leaf Al	0.11	0.70	0.65	0.01	0.43	0.03	0.35	0.10			0.62	0.01
Leaf Na	0.18	0.50	0.59	0.01	0.30	0.10	0.11	0.60			0.80	0.01
Population	0.06	0.80	−0.64	0.01	−0.58	0.01	−0.44	0.03			−0.81	0.01
Height	0.44	0.10	−0.90	0.01	−0.71	0.01	−0.70	0.01			−0.82	0.01
Node	0.24	0.40	−0.52	0.02			−0.24	0.30			0.15	0.50
Pod	0.28	0.30	−0.68	0.01			−0.26	0.20			−0.03	0.90
Seed size	−0.25	0.40	0.54	0.01			−0.01	0.90			0.41	0.04
Grain oil	0.49	0.50	0.25	0.02			0.03	0.90			−0.10	0.70
Grain protein	0.05	0.90	0.52	0.30			−0.31	0.20			0.04	0.80
Grain yield	0.21	0.50	−0.81	0.01	−0.49	0.01	−0.77	0.01			−0.64	0.01

At the R1 stage, mean plant height in the unflooded plots varied between 58 and 94 cm at the different sites (Fig. 2). Correlations between plant height and flooding duration were observed at four of the sites. Generally, the longer the flooding duration, the shorter the plants. At the CH site, plant height was not affected even after 6 d of flooding. Flooding for 8 d occurred only at the FR site and the plants in this area were only 20 cm tall.

The grain yield of each flooding duration and each site are shown in Fig. 3. At the CH site, flooding for up to 6 d showed no reduction of soybean grain yield. Yield at the P1, P2, and UN sites remained unchanged after 3 d of flooding, while yield at the FR and UN sites was reduced by 65 and 93%, respectively, after 6 d of flooding as compared to the nonflooded control.

Additional details about the correlations of flooding duration and soil and plant parameters at each site are reported in Tables 7 and 8, respectively, and are discussed below.

Champaign Site

The association between flooding duration and yield and plant parameters was not detected at this site. No change in yield (Fig. 3) and plant parameters (Table 8) was found, even in plots flooded for up to 6 d. Soil from areas flooded for 6 d had higher P, K, Ca, Mg and Mn than nonflooded soil, while soil from areas flooded for 3 d only showed higher Ca and Mg than nonflooded soil (Table 7).

Franklin Site

The flooded plots at this site remained flooded for more than 3 d. Plant height (Fig. 2) and yield (Fig. 3) were less for plants flooded for 6 and 8 d compared with nonflooded plants. Leaf tissue N concentration was less in plants flooded for 8 d than in nonflooded plants while leaf tissue concentrations of K, Ca, Mg, Fe, and Al were higher (Table 8). Similar results were also found

Table 7. Comparisons of soil elemental concentrations and other soil parameters between flooding durations at each site.

Site	CH			FR			P1		UN			FA		P2		
Flooding duration (d)	0	3	6	0	6	8	0	3	0	3	8	0	3	0	3	6
Elements (mg kg^{-1})																
P	65b†	82b	117a	91a	107a	105a	30a	36a	67a	72a	91a	30a	33a	101a	36b	31b
K	283b	305b	348a	149a	154a	167a	137a	161a	205a	217a	223a	167a	155a	151a	124a	121a
Ca	3273b	3995a	3835a	2892b	3613ab	4166a	2229a	2351a	4346a	4520a	4700a	3045b	3879a	1958c	2745b	3550a
Mg	643b	852a	858a	370a	331a	349a	387a	432a	915a	911a	960a	682b	932a	415a	395ab	321b
Mn	61b	72ab	80a	91b	119ab	123a	78a	93a	105a	107a	104a	60a	58a	79b	83b	114a
B	1a	1a	1a	1a	1a	1a	1a	1a	1a	1a	1a	1a	1a	1a	1a	<1a
Zn	4a	7a	4a	12b	21ab	27a	7a	7a	7a	5a	5a	5a	6a	4b	5b	15a
Parameters																
OM (g kg^{-1})	60a	60a	60a	40a	40a	40a	30a	30a	60a	60a	60a	60a	70a	30a	30a	40a
CEC (meq 100 g^{-1} soil)	24a	27a	27a	18c	21b	24a	15a	16a	30a	29a	32a	25b	28a	14b	17b	21a
pH	7b	8a	8a	8a	8a	8a	7a	7a	8a	8a	8a	7a	7a	8a	8a	8a

† Means within each site not followed by the same letter are statistically different at $p < 0.05$.

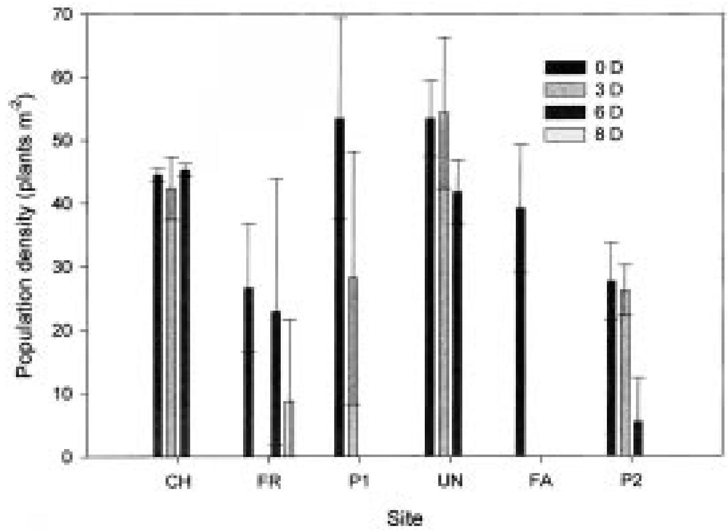

Fig. 1. The plant population associated with different flooding durations at each site. Standard errors of each mean are presented as vertical bars.

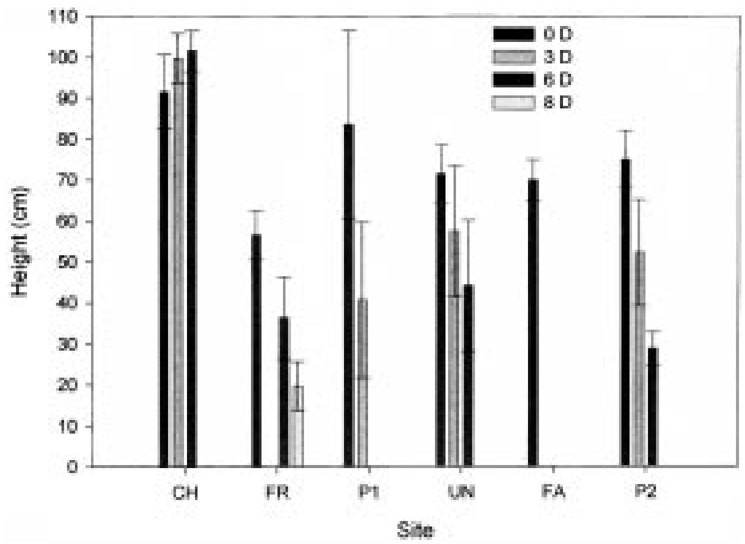

Fig. 2. The plant height associated with different flooding durations at each site. Standard errors of each mean are presented as vertical bars.

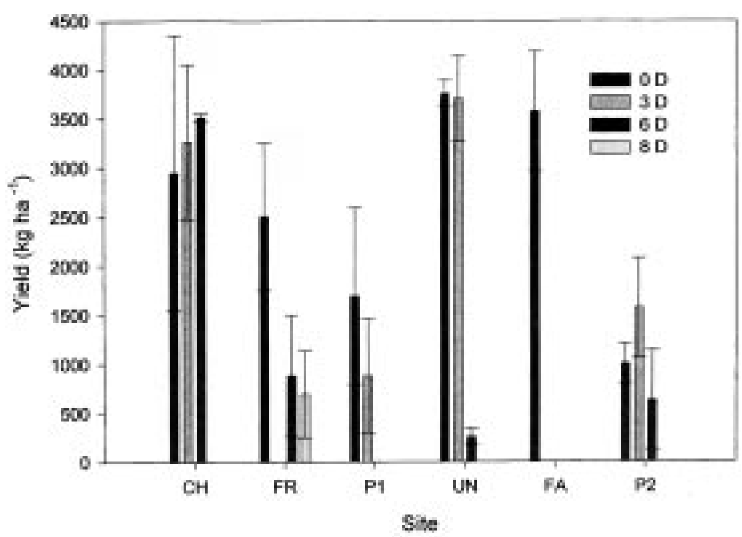

Fig. 3. The grain yield associated with different flooding durations at each site. Standard errors of each mean are presented as vertical bars.

Table 8. Comparisons of leaf elemental concentrations and other plant parameters between flooding durations at each site.

Site	CH			FR			P1		UN			FA	P2		
Flooding duration (d)	0	3	6	0	6	8	0	3	0	3	6	0	0	3	6
Elements	g kg^{-1}														
N	60a†	60a	60a	60a	50b	50b	60a	50a	60a	60a	60a	60	50a	50a	50a
P	4a	3a	4a	4a	4a	4a	4a	4a	.05a	.05a	.05a	4	4b	4b	5a
K	21a	20a	20a	19b	21ab	22a	19a	20a	2a	2a	2a	22	14a	13a	15a
Ca	8a	8a	9a	10b	12a	12a	9b	10a	0.9a	0.9a	0.9a	7	11c	12b	16a
Mg	3a	3a	3a	4b	4b	5a	4a	4a	0.4a	0.5a	0.5a	4	5a	5a	6a
Mn	0.05a	0.04a	0.04a	0.04a	0.05a	0.04a	0.05a	0.05a	0.04a	0.04a	0.04a	0.05	0.06a	0.06a	0.05a
Fe	0.1a	0.1a	0.1a	0.1b	0.1b	0.2a	0.1a	0.1a	0.1a	0.1a	0.1a	0.1	0.1a	0.1a	0.2a
B	0.04a	0.04a	0.04a	0.06a	0.06a	0.05a	0.05a	0.05a	0.06a	0.06a	0.06a	0.05	0.04b	0.05a	0.05a
Cu	0.01a	0.01a	0.01a	0.01a	0.01a	0.01a	0.01a	0.01a	0.01a	0.01a	0.01a	0.009	0.009b	0.01a	0.01a
Zn	0.04a	0.04a	0.04a	0.005a	0.005a	0.005a	0.006b	0.004a	0.005a	0.006a	0.005a	0.04	0.02c	0.05b	0.07a
Al	0.02a	0.02a	0.02a	0.01c	0.04b	0.2a	0.02a	0.06a	0.02a	0.03a	0.02a	0.01	0.02a	0.02a	0.1a
Parameters‡															
Oil content (g kg^{-1})	210a	210a	210a	200a	210a	200a	N/A	N/A	200a	220a	200a	190	190a	200a	190a
Protein content (g kg^{-1})	420a	420a	420a	400a	410a	420a	N/A	N/A	420a	410a	410a	420	440a	430a	430a
Pod number	36a	40a	42a	50a	38a	32a	N/A	N/A	47a	43a	41a	51	25a	42a	31a
Seed size	15a	15a	14a	12a	13a	13a	N/A	N/A	15a	15a	14a	13	11a	11a	12a

† Means within each site not followed by the same letter are statistically different at $p < 0.05$.

‡ Pod number expressed as number of total pods with at least one seed. Seed size expressed as gram per 100 seeds.

in plants flooded for 6 d, except for the leaf K concentration that was not different from the nonflooded plants. Soil concentrations of Ca, Mn, and Zn and the CEC were higher in soil flooded for 8 d compared with nonflooded soil (Table 7).

Pickaway 1 Site

Flooding at this site was brief. After 3 d of flooding, plants were shorter (Fig. 2), but the flooding did not significantly reduce the population (Fig. 1) and yield (Fig. 3) compared with the nonflooded plants. Leaf tissue Ca and Mg concentrations were higher in the flooded plants compared with the nonflooded plants, while leaf tissue Zn concentration was lower (Table 8). None of the soil parameters differed due to flooding duration (Table 7).

Union Site

No difference in plant population was detected at this site due to flooding duration; however, plant height (Fig. 2) and grain yield (Fig. 3) were smaller with 6 d flooding compared with the nonflooded plants. There were no significant differences in any other plant or soil parameters due to flooding duration (Tables 7 and 8).

Fayette Site

The flooding at this site was caused by stream overflow. The flooding was brief (3 d), but the plants were thickly coated with sediment. The plants did not recover and died soon after the flooding, thus, no yield and plant parameters were measured at this site. Soil Ca and Mg concentrations and the CEC were greater in the flooded area compared with the nonflooded areas (Table 7).

Pickaway 2 Site

The flooding at this site was caused by a major river overflow and persisted for up to 6 d. Plant population (Fig. 1) and plant height (Fig. 2) were reduced in the 6 d flooding plots as compared with the nonflooded plots, but no difference in yield was detected (Fig. 3). Plant height in the 3 d flooding plots was also reduced (Fig. 2), but plant population and yield did not differ from the nonflooded plots. Leaf tissue P, Ca, Mg, B, Cu, and Zn concentrations were all higher in plants flooded for 6 d compared with nonflooded plants (Table 8). Leaf tissue Ca and B were also higher in plants flooded for 3 d than in nonflooded plants (Table 8). Generally, the soil P and Mg concentrations were lower in flooded plots than in nonflooded plots, while the soil Ca, Mn, and Zn concentrations and the CEC were higher (Table 7).

DISCUSSION

The 1998 growing season in Central Ohio was very wet in June, creating flooding at all six of the sites studied, and very dry in August, resulting in drought stress at most of the sites. Our study reported a 20% reduction in soybean grain yield associated with 3 d of flooding at the V2 and V3 stage. Up to 93% yield loss was detected after 6 d of flooding. Similar results were reported by Heatherly and Pringle (1991) in a three-year study of soybean cultivars' response to flood irrigation. According to these authors, flood irrigation for >2 d may reduce soybean yield by 20% as compared with a 1 d flood irrigation treatment.

The type of flooding, stream overflow vs. low land depressional, may impact the severity of stresses and yield reduction differently. Sediments carried by stream flooding at the FA and P2 sites were deposited on the leaves of flooded plants. The silt-covered leaves wilted severely after flooding. At the P2 site, light rain three days after flooding washed the sediment off the leaves enabling the plants to recover substantially. At the FA site, the plants died before the sediment was washed off the leaves.

The yield reduction associated with flooding in this study may be attributed to lower plant population, shorter plant height, and fewer pods per plant (Table 6). According to Linkemer et al. (1998) the effects of waterlogging on yield components differed depending on the growth stage. They reported yield loss caused by waterlogging at R5 was due to decreased seed size, while waterlogging at R1 caused fewer pods per reproductive node, and at V2 resulted in lower branch number.

In this study, no change in plant population, plant height, leaf elemental concentrations and grain yield was detected in plots that were waterlogged for up to 6 d at the CH site. The subsoil at the CH site has high sand content (data not shown) and when drained, the root zone quickly returns to an aerated condition. This natural subsurface drainage reduced root zone waterlogging and its damage on soybean plant growth and grain yield. Similar effects are achieved by man-made subsurface drainage to improve crop yield in poorly drained soil (Schwab et al., 1975). Near normal rainfall in August at this site also eliminated a secondary stress present at the other sites.

The lack of injuries at the CH site could also be because of a greater flooding tolerance of the soybean cultivar grown at that site. Heatherly and Pringle (1991) reported that Sharley soybean was more tolerant to flood irrigation than Centennial soybean. Variation in tolerance to flooding was also detected in a field study of 84 soybean genotypes (VanToai et al., 1994).

Flooding for 3 d did not change the yield at the Union site, but increased yield by 56% at the P2 site (Fig. 3). The lack of yield loss due to flooding may have been caused by greater residual soil moisture associated with a flooded area when drought stress occurred in August and September at these two sites. According to Jones et al. (1989), in drought years significant differences in grain yield were found among soybean fields of different elevations. Soybeans on the low interfluve produced higher yield than soybeans on the shoulder or summit where drought stress was greater.

Despite the wide variation in soil types, plant varieties, and weather conditions, some consistent trends in leaf elemental concentration changes due to flooding were detected in our study. The reduction in N concentrations and the increase in P, Ca, Mg, B, Fe, Cu, and Al in flooded soybean leaves reported in our study were similar to the results reported by Fausey et al. (1985) for corn seedling leaves. Flooding has been known to cause nutrient imbalance and mineral toxicity in plants (Barrick and Noble, 1993).

In addition, the plant, soil, and weather results collected in this study are being used in a statistical model to determine the interactions of these factors in reducing soybean grain yield. The determining factor(s) that reduces soybean yield in flooded fields, once identified, will assist in the development and testing of flood tolerant varieties, and also in the decision making process of how to best cope with flooding problems using precision agriculture technology.

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Straw Production and Grain Yield Relationships in Winter Wheat

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ABSTRACT

Winter wheat (*Triticum aestivum* L.) –fallow is the predominant cropping system in low-precipitation regions (<250 mm annually) of the inland Pacific Northwest (PNW) in the USA. Wind erosion is a recurrent problem during and after fallow periods when inadequate crop residue amounts are retained on the soil surface. Management options that optimize both grain yield and straw production are needed. A 3-yr field study was conducted to determine sowing rate and sowing date effects on straw and grain yield, and grain yield components of winter wheat cultivars with semidwarf, standard height, or tall growth habit. Four winter wheat cultivars were evaluated at three sowing rates (65, 130, and 195 seeds m^{-2}) and three sowing dates in August, September, and October. A split plot design was used, with sowing dates as main plots and sowing rate × cultivar combinations as subplots. The greatest effect of sowing date was on straw production. Straw biomass from mid-August sowing averaged 6.70 Mg ha^{-1} compared with 4.65 and 2.78 Mg ha^{-1} from mid-September and mid-October sowing, respectively. Grain yield was highest for mid-August sowing during two years and lowest for mid-October sowing all years. Averaged across years, the semidwarf cultivar produced the highest grain yield on all sowing dates and was equal to the standard height and tall cultivars for straw production. Path coefficient analysis showed that variation in grain yield was due primarily to differences in spikes per unit area (SPU) and kernels per spike (KPS). Late sowing resulted in a large reduction in SPU and, therefore, grain yield. For cropland susceptible to wind erosion in east-central Washington, early sowing results in increased wheat straw production and generally higher grain yield compared with mid-to-late sowing dates.

Residue on the soil surface is often the only protection against wind erosion on poorly aggregated soils in the 150- to 250-mm annual precipitation dryland wheat production zone of east-central Washington. Winter wheat–fallow is the dominant cropping pattern in use. Growers often have difficulty maintaining the minimum (390 kg ha^{-1}) residue cover on the soil surface because of the low quantities of straw produced and the use of traditional intensive tillage practices during fallow (Papendick, 1998). During most years, use of summer fallow allows growers to sow winter wheat into adequate carryover soil water for seed germination during mid-to-late August. Sowing must sometimes be delayed due to insufficient seed–zone soil water (Schillinger et al., 1998), or the need to control winter annual grass weeds (Ogg, 1993). Early stand establishment is an important factor for increasing grain yield, and it is strongly influenced by seed–zone water content and depth of soil covering the seed (Lindstrom et al., 1976). Because of frequent dry seed–zone conditions and the need for seedlings to emerge from deep sowing depths, tall and standard height cultivars predominate in east-central Washington, while only the best-emerging semidwarf cultivars are grown (Donaldson, 1996).

Harvest index (HI) is defined as percentage grain in the total plant biomass. Genetic improvement of grain yield in winter wheat has been closely associated with increases in HI, but not with increases in total biomass (Slafer and Andrade, 1991). Thus, the adoption of semidwarf wheat cultivars is due to their increased biological efficiency, as these shorter cultivars tend to produce less straw per unit of grain than conventional height cultivars. Wallace et al. (1993) warned that the trend of achieving higher grain yield by increasing HI is not sustainable, and recommended total biomass be considered in breeding programs to assure long-term yield improvement.

Sowing rate and date effects on grain yield of wheat have been reported from major wheat-producing regions in the USA and Canada (Paulsen, 1987). Of the three grain yield components — SPU, KPS, and kernel weight (KW) — SPU and KPS generally are the most important determinants of grain yield (Knapp and Knapp, 1978; Shah et al., 1994). Although KW does exert an influence on grain yield, numerous sowing rate experiments have demonstrated that its influence is generally smaller than that of SPU or KPS (Guitard et al., 1961; Shah et al., 1994). Maximum grain yield results from an optimum balance of the three yield components,

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Abbreviations: HI, harvest index; KPS, kernels per spike; PNW, Pacific Northwest; SPU, spike number per unit area; KW, kernel weight.